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MASSIVE NEUTRINOS AND COSMOLOGY

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Cosmology can provide information on the absolute scale of neutrino masses, complementary to the results of tritium beta decay and neutrinoless double beta decay experiments. We show how the analysis of data from the anisotropies of the cosmic microwave background radiation and from the distribution of cosmological large-scale structure, combined with other experimental results, provides an upper bound on the sum of neutrino masses. We also discuss the sensitivity of future cosmological data to neutrino masses.

1 Introduction

Neutrinos are very abundant in the universe, in number only slightly smaller than that of relic photons. After being created in earlier epochs, relic neutrinos influence various cosmological stages, playing an important role that has been used to derive bounds on non-standard neutrino properties, alternative to the limits from terrestrial neutrino experiments, in some cases the only available. For an extensive review on many aspects of neutrino cosmology, see e.g. [1].

In this contribution we focus on the connection between cosmology and neutrino masses, reviewing recent cosmological bounds on the sum of neutrino masses, in particular those that appeared after the release of the first year data of the Wilkinson Microwave Anisotropy Probe (WMAP) [2]. We also discuss how future cosmological observations will improve the sensitivity to neutrino masses in the sub-eV region.

2 The cosmic neutrino background

In the early universe neutrinos were in thermal equilibrium through the standard weak interactions with other particles. Thus the distribution of neutrino momenta was a Fermi-Dirac

one,

$$f_{\nu_\alpha}(p) = \left[\exp\left(\frac{p-\mu_{\nu_\alpha}}{T}\right)+1\right]^{-1}~, \tag{1}$$

for neutrino masses much smaller than the temperature. The chemical potentials of the different neutrino flavours μ_{ν_α} could have been non-zero if an asymmetry between the number of neutrinos and antineutrinos was previously created. Although this lepton asymmetry can still be very large compared to the baryon one, it has been shown [3] that in practice due to the effectiveness of flavour neutrino oscillations before the onset of primordial nucleosynthesis, it can be safely neglected.

As the universe cools, at a temperature $T_{\rm dec} \simeq \mathcal{O}(\text{MeV})$ the weak interaction rate Γ_ν falls below the expansion rate given by the Hubble parameter H and neutrinos decouple from the rest of the plasma. After decoupling, the collisionless neutrinos expand freely, keeping a phase-space density corresponding to that of a relativistic species in equilibrium, and do not essentially share the entropy transfer from e^+e^- annihilations into photons that causes the well-known temperature difference $T_\gamma/T_\nu = (11/4)^{1/3}$ between relic photons and relic neutrinos [a]. It is thus easy to calculate the number and energy densities of relic neutrinos at later epochs. The former is fixed by the value of the temperature (approximately there are now 112 neutrinos and antineutrinos per flavour and cm^{-3}), but the energy density is a function of the mass that should be in principle calculated numerically, with the analytical limits

$$\begin{aligned}\rho_\nu(m_\nu \ll T_\nu) &= \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4 \\ \rho_\nu(m_\nu \gg T_\nu) &= \sum_i m_i\, n_\nu \end{aligned} \tag{2}$$

where the sum runs over all neutrino states for which $m_i \gg T_\nu$. For values of neutrino masses much larger than the present cosmic temperature ($T_\gamma \sim T_\nu \approx 10^{-4}$ eV), one finds that the contribution of neutrinos to the total energy density of the universe is, in terms of its critical value ρ_c,

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93.2\, h^2~\text{eV}} \tag{3}$$

where $h \equiv H_0/(100~\text{km s}^{-1}~\text{Mpc}^{-1})$ is the present value of the Hubble parameter.

3 Neutrinos as dark matter

The role of neutrinos as dark matter (DM) particles has been widely discussed since the 1970s. Two facts favour massive neutrinos as DM: they definitely exist and it is enough to have eV masses in order to produce a contribution of order unity to the present energy density of the universe. From Eq. 3 one easily finds an upper limit on the masses (some tens of eV) by imposing the very conservative bound $\Omega_\nu < 1$.

The background of relic massive neutrinos affects the evolution of cosmological perturbations in a particular way: it erases the density contrasts on wavelengths smaller than a mass-dependent free-streaming scale. This damping of the density fluctuations on small scales is characteristic of hot dark matter (HDM) particles. In a universe dominated by HDM, large objects such as superclusters of galaxies form first, while smaller structures like clusters and galaxies form via a fragmentation process (a top-down scenario). However, within the presently favoured ΛCDM model, dominated at late times by dark energy and where the main matter component

[a] Some residual interactions between e^+e^- and neutrinos lead to small distortions on the neutrino spectra with respect to that in Eq. 1. The effect over the relativistic degrees of freedom corresponds to $N_{\rm eff} = 3.045$ (see [4,5] for the latest analyses and previous references).

is pressureless, there is no need for a significant contribution of HDM. Therefore, one can use the available cosmological data to find how large the neutrino contribution can be. If all neutrino states have the same spectrum, as in the standard cosmological model, an analysis of the data will provide an upper bound on the sum of all neutrino masses.

This bound is important because presently we have experimental evidences of flavour neutrino oscillations, which are sensitive to the squared mass differences between the three neutrino mass states $m_{1,2,3}$: allowed 3σ ranges are $\Delta m^2_{23} = (1.4 - 3.3) \times 10^{-3}$ eV^2 and $\Delta m^2_{12} = (7.2 - 9.1) \times 10^{-5}$ eV^2 (see e.g. [6,7] and references therein). These values are perfectly compatible with a hierarchical scenario where the neutrino massive states have $m_1 \sim 0$, $m_2 \sim (\Delta m^2_{12})^{1/2}$ and $m_3 \sim (\Delta m^2_{23})^{1/2}$ (or with an inverted hierarchy where $m_3 \sim m_2 \sim (\Delta m^2_{23})^{1/2}$, separated by the small Δm^2_{12}, see e.g. Fig. 1 in [8]). The sum of neutrino masses would then be of the order $\sum_i m_i \simeq m_3 \sim 0.05$ eV (or $\sum_i m_i \simeq m_3 + m_2 \sim 0.1$ eV in the inverted case). Alternatively, the three states could be degenerate, with masses much larger than the differences, so that $\sum_i m_i \simeq 3m_0$.

Cosmology is at first order sensitive to the total mass if all neutrino states have the same number density, providing information on m_0 but blind to neutrino mixing angles or possible CP violating phases. This fact differentiates cosmology from terrestrial experiments such as beta decay and neutrinoless double beta decay [9], which are sensitive to $\sum_i |U_{ei}|^2 m_i^2$ and $m_{ee} \equiv |\sum_i U_{ei}^2 m_i|$, respectively ($U$ is the 3×3 mixing matrix that relates the weak and mass bases). Presently, from tritium beta decay one finds $m_0 < 2.2$ eV (95% CL), a bound expected to be improved by the KATRIN project to reach $0.3 - 0.35$ eV [10]. We also have results on m_{ee} from neutrinoless double beta decay experiments, which give upper bounds in the range $0.3 - 1.6$ eV and a claim of positive evidence for m_{ee} [11]. However, these results suffer from the uncertainties in the calculations of the corresponding nuclear matrix elements (for a review, see e.g. [12]).

4 Current cosmological bounds on neutrino masses

For neutrino masses of order eV, the free-streaming effect can be detectable in the linear matter power spectrum, reconstructed from galaxy redshift surveys (a rough analytical approximation of the effect is $\Delta P(k)/P(k) \sim -8\Omega_\nu/\Omega_m$ [13], usually quoted in the literature). Massive neutrinos have also a smaller background effect: different values of the neutrino density fraction Ω_ν have to be compensated by small changes to the other components, modifying some characteristic times and scales in the history of the universe, like the time of equality between matter and radiation, or the size of the Hubble radius at photon decoupling. Although neutrino masses influence only slightly the spectrum of the anisotropies of Cosmic Microwave Background (CMB) radiation, it is crucial to combine CMB and large-scale structure (LSS) observations, as well as other cosmological observations, in order to measure the neutrino mass, because CMB data give independent constraints on the cosmological parameters, and partially removes the parameter degeneracies.

We show in Table 1 a summary of recent results from analyses of cosmological data, which emphasizes the fact that a single cosmological bound on neutrino masses does not exist. Assuming that the relic neutrinos are standard, the limits depend on the underlying model (the set of cosmological parameters) and the cosmological data used. The data include CMB experiments (WMAP, other CMB such as ACBAR and CBI) and different LSS data: the distribution of galaxies from 2dFGRS or the Sloan Digital Sky Survey (SDSS), the *bias* (normalization of the matter power spectrum, for instance through a parameter such as σ_8) or the matter power spectrum on small scales inferred from the Lyman-α forest. In addition, other cosmological data can be incorporated via priors on parameters such as h (HST) or Ω_m (SNI-a data). For details, we refer the reader to the discussion in [17].

Table 1: Upper bounds on $\sum m_\nu$ from recent analyses of different sets of cosmological data.

Ref.	Bound on $\sum m_\nu$ (eV, 95% CL)	Data (in addition to WMAP)
14	2.0	–
15	1.7	SDSS
16	1.0	other CMB, 2dF, HST, SN
17	1.0 [0.6]	other CMB, 2dF, SDSS [HST, SN]
18	0.75	other CMB, 2dF, SDSS, HST
19	0.7	other CMB, 2dF, σ_8, HST
20	0.47	other CMB, 2dF, SDSS (Ly-α), HST, SN
21	0.42	SDSS (bias, galaxy clustering, Ly-α)

It is important to emphasize that not all the analyses in Table 1 used the same set of cosmological parameters and priors (such as the assumption of a flat Universe), so that minor differences on the quoted bounds exist even when using the same cosmological data. Actually there exist some works where non-zero neutrino masses could be either favoured by cosmology if radical departures from the *standard* ΛCDM model are considered (see e.g. [22]) or needed to fit some particular data, as in [23] where the region of allowed neutrino masses was found to be $\sum m_\nu = 0.56^{+0.30}_{-0.26}$ eV when using a a low value of the normalization of the matter power spectrum from X-ray cluster data. These examples show that the sensitivity of cosmological observations to neutrino masses is a powerful tool, but its implications should not be extracted without care.

One can see from Table 1 that a conservative cosmological bound on $\sum m_\nu$ of the order 1 eV was found from CMB results combined only with galaxy clustering data from 2dFGRS and/or SDSS (i.e. the shape of the matter power spectrum for the relevant scales). The addition of further data via priors improves the bounds, which reach the lowest values when Lyman-α data (from SDSS) are included as in refs. [21,20]: the contribution of a total neutrino mass of the order 0.4-0.5 eV seems already disfavoured.

An interesting case of degeneracy between cosmological parameters is that between neutrino masses and the radiation content of the universe (parametrized via the effective number of neutrinos $N_{\rm eff}$). The extra radiation partially compensates the effect of neutrino masses, leading to a less stringent bound on $\sum m_\nu$ [16,17,24], as shown in Fig. 1. This applies to the neutrino mass schemes that also explain the results of LSND, an independent evidence of neutrino conversions at a larger mass difference than those quoted in the previous section, where a fourth sterile neutrino is required with mass of $\mathcal{O}$(eV) [7]. At present, the LSND regions in the space of oscillation parameters (that will be checked by the ongoing MiniBoone experiment [25] are not yet completely disfavoured by cosmological data.

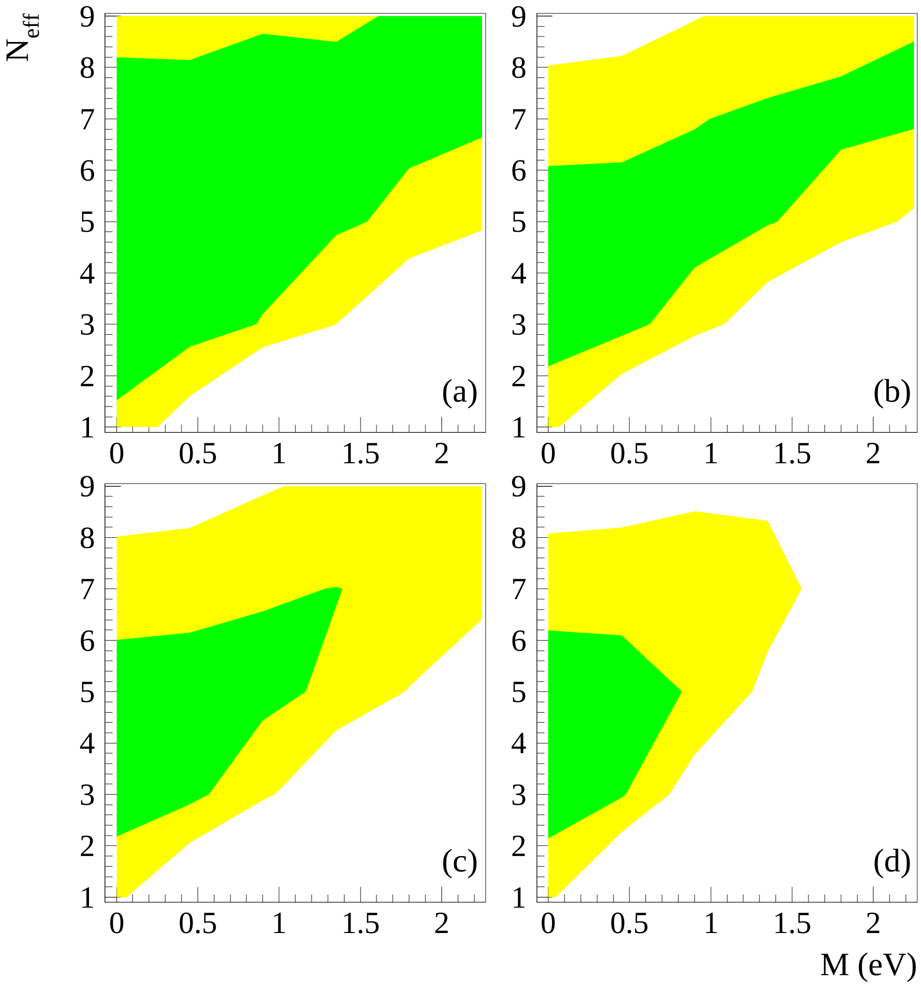

Figure 1: Two-dimensional likelihood in ($N_{\rm eff}, M \equiv \sum m_\nu$) space, marginalized over the other cosmological parameters of the model. We plot the 1σ (green / dark) and 2σ (yellow / light) allowed regions. Here we used CMB (WMAP & ACBAR) and LSS (2dF & SDSS) data, adding extra priors on h (HST) and Ω_m (SN99 or SN03) as follows: (a) no priors, (b) HST, (c) HST+SN99, (d) HST+SN03. For details, see ref. [17].

Finally, let us remind the reader that the cosmological implications of neutrino masses could be very different if the spectrum or evolution of the cosmic neutrino background is non-standard. For instance, the bounds on neutrino masses would be modified if relic neutrinos have non-thermal spectra [26] or violate the spin-statistics theorem obeying Bose statistics [27], or could almost completely disappear, such as for the case of mass varying neutrinos (see e.g. [28] and references therein).

5 Future sensitivities to neutrino masses from cosmological observations

Future CMB data from WMAP and Planck, combined with LSS data from larger galaxy surveys will enhance the cosmological sensitivity to neutrino masses. The pioneering calculation in ref. [13] found that the combination of Planck and SDSS data will push the bound on $\sum m_\nu$ to approximately 0.3 eV at 95% CL. An updated forecast analysis [29] lowered this value to 0.12 eV, almost reaching the values in the hierarchical scenarios of neutrino masses, but a recent work [8] has shown that some approximations in [29] (such as taking the errors of CMB data given only by cosmic variance) were too crude. A more conservative estimate [8] for experimental data

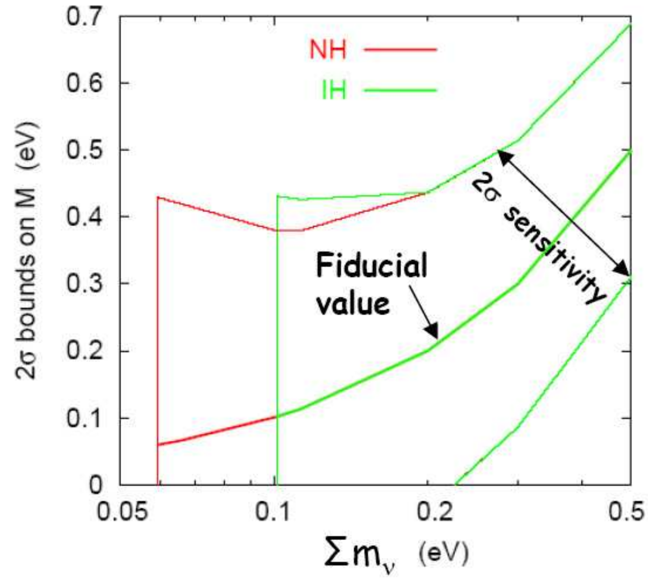

Figure 2: Predicted 2σ error on the total neutrino mass $M \equiv \sum m_\nu$ as a function of M in the fiducial model, using future data from PLANCK and SDSS (limited to $k_{\rm max} = 0.15\ h\ {\rm Mpc}^{-1}$). The case NH (IH) corresponds to three massive neutrino states where the total neutrino mass is distributed according to a normal (inverted) hierarchy. For details of the analysis, see ref. [8].

available approximately at the end of the present decade is 0.21 eV for Planck+SDSS, that could be improved to 0.13 eV with data from CMBpol (a project of a future CMB satellite with better sensitivity to CMB polarization). As an example, we show in Fig. 2 the predicted sensitivity for Planck+SDSS at 2σ on the sum of neutrino masses as a function of the assumed fiducial value. Note that the possible values of $\sum m_\nu$ are of course bounded from below: the minimal value corresponds to the limit in which the lightest neutrino mass goes to zero (different for normal or inverted hierarchy schemes).

Other cosmological probes of neutrino masses could reach similar or even better sensitivities in the next future. To probe the mass distribution of the universe one can use either the weak gravitational lensing of background galaxies by intervening matter [30] or the distortions of CMB temperature and polarization spectra caused by gravitational lensing [31]. These two methods are potentially sensitive to neutrino masses of the order 0.1 eV, while the combination of both could improve it possibly down to the minimum values expected in the hierarchical neutrino schemes, as recently shown in [32].

6 Conclusions

Cosmological data can be used to bound the sum of neutrino masses, providing information on the absolute neutrino mass scale that is complementary to terrestrial experiments such as tritium β decay and neutrinoless double β decay experiments. We have briefly described the effects of massive neutrinos on the evolution of the Universe. The subleading contribution of massive neutrinos to the cosmological matter content has been analyzed in recent works, in particular after the the release of the first year WMAP data.

Current cosmological bounds on the sum of neutrino masses are in the range $0.42 - 1.7$ eV (at 95% CL), which depend both on the included data and the assumed set of cosmological parameters. These values prove the region where all neutrino mass states are degenerate, but future cosmological data will provide sub-eV sensitivities in the coming years which could test the quasi-degenerate region of neutrino masses and eventually the minimum values in the hierarchical

scenarios, in particular in the inverted case.

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